Advanced fuel designs for existing and future reactors: driving factors from technical and economic points of view

Kevin Hesketh

BNFL Nuclear Science & Technology Services

FISA-2003, Luxembourg 10-13 November 2003

Plan

- Reviews current state of advanced fuel design development :
  - evolutionary fuel design developments for LWRs
  - radical fuel design developments for LWRs
  - fuel development for future thermal reactor systems
  - fuel designs for future fast reactor systems

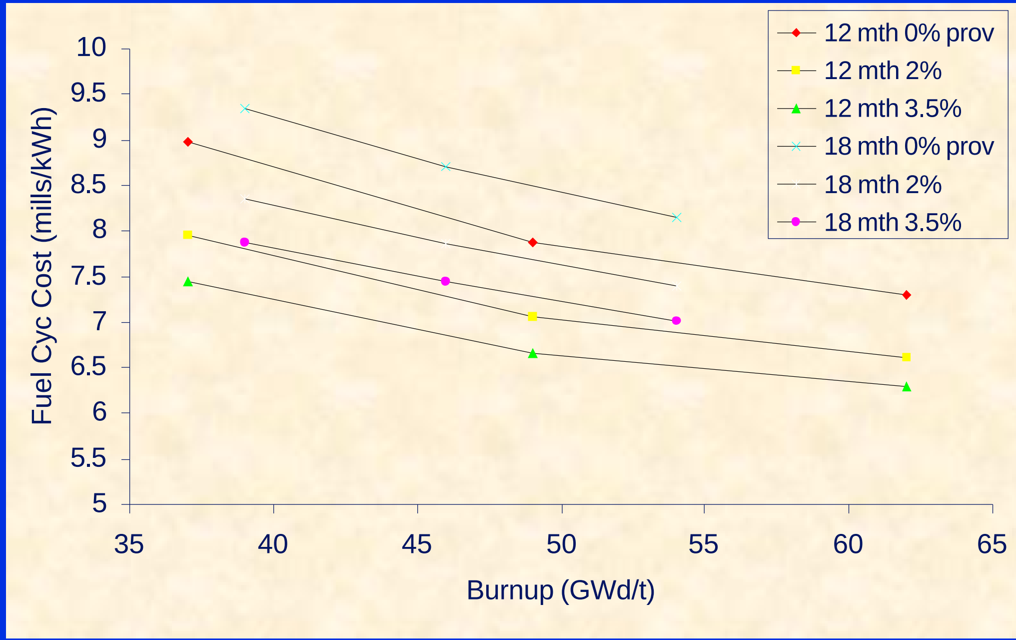
Evolutionary fuel design developments for LWRs

BNFL

- Emphasis on low development risk and basing on known experience wherever possible
- Principal driver for the utilities is fuel reliability :
  - –utilities need to ensure reactor output not limited by fuel issues
  - –fuel is only a small fraction (~ 15% to 20%) of total generating costs
  - –fuel cost reduction is secondary to generating cost reduction
- Fuel failure rate target < 1 failure in 10^5 rods
  - –difficult to demonstrate with a new design

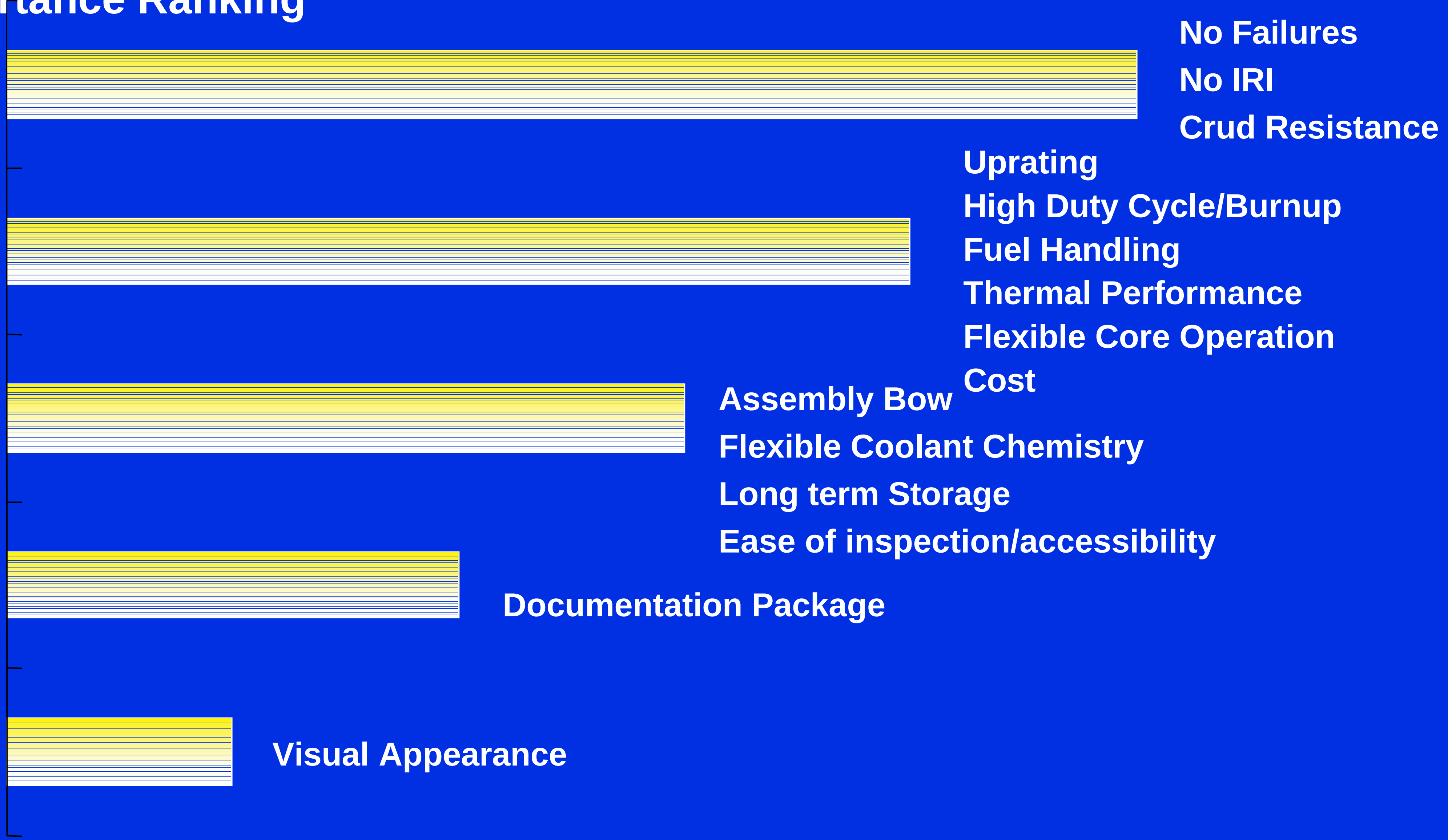
Evolutionary fuel design developments for LWRs

- Secondary driver for utilities is extending discharge burnups :
  - –burnup extension generally reduces fuel cycle costs :
- Many utilities wish to increase cycle lengths to improve overall load factor :
  - –24 month cycle lengths being considered in the US
  - –drives down overall generating cost even though fuel costs penalised



Customer Needs

ortance Ranking

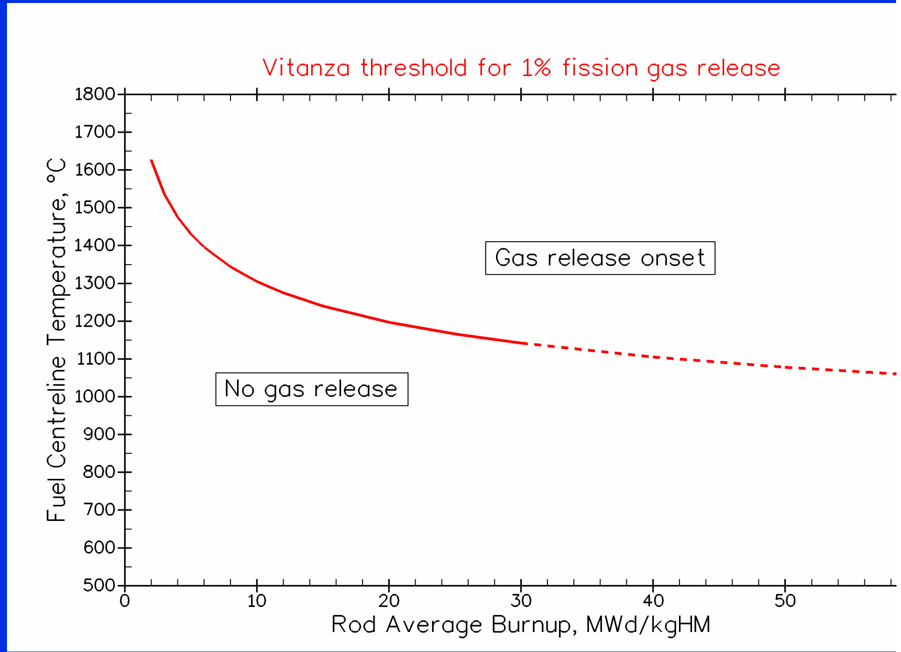


Fuel development timescales

- Irradiation tests take several years to complete and to follow up with post-irradiation examination etc
- Followed by lead test assemblies in commercial plant, again lasting several years
- Then gradual follow-up with large lead loadings
- Some scope for parallel programming, but development timescales from beginning to demonstrated product are typically 10 to 20 years
- Risks lead fuel vendors and utilities to be very conservative
  - –radical design innovations are seldom welcomed

LWR fuel pellet

- UO_2 or PuO_2/UO_2 pellet manufacturing know-how continually being improved
- Principal life limiting mechanism is fission gas release
  - –determined by Vitanza threshold
  - –many variable factors that would benefit from improved understanding
  - –positive feedback mechanism eventually causes failure
  - –exponential-type dependence on discharge burnup

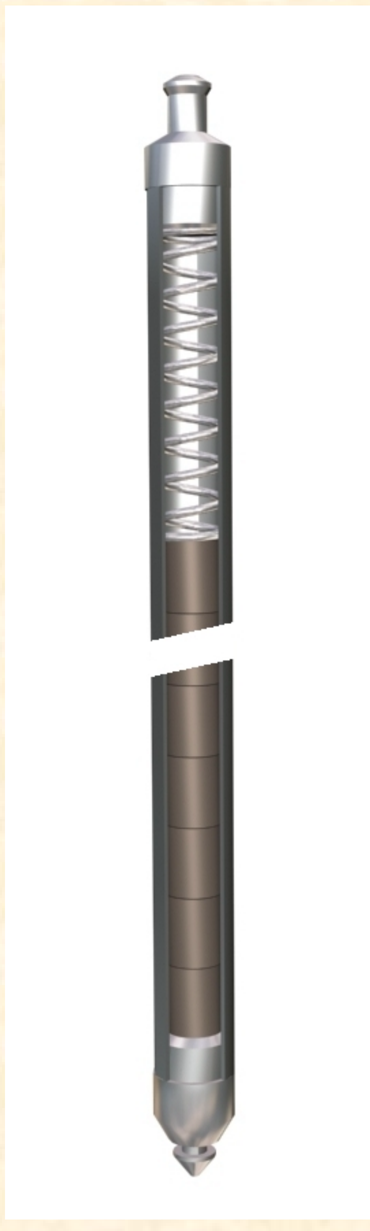


LWR fuel pellet

- Other life-limiting mechanisms include :
  - –pellet swelling
  - –rim effect causes localised micro-structural changes near the pellet periphery
- Improved understanding of precise dependencies on pellet micro-structure and fabrication process needed
- Pellet additives have the potential to improve pellet properties eg. Niobia doping to soften pellet and reduce impact of pellet clad interaction failure

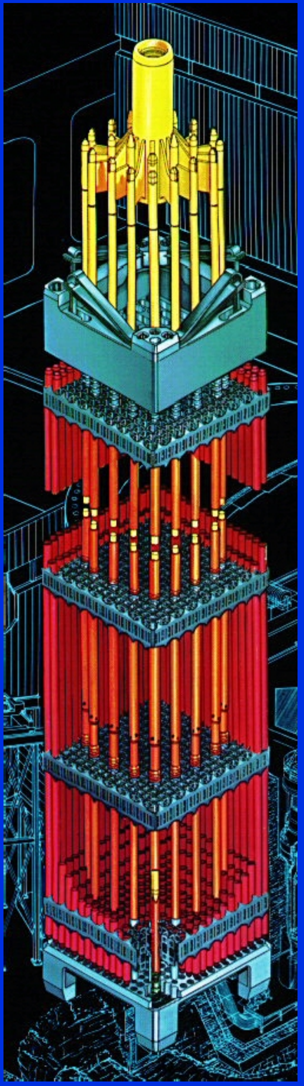
LWR fuel rod

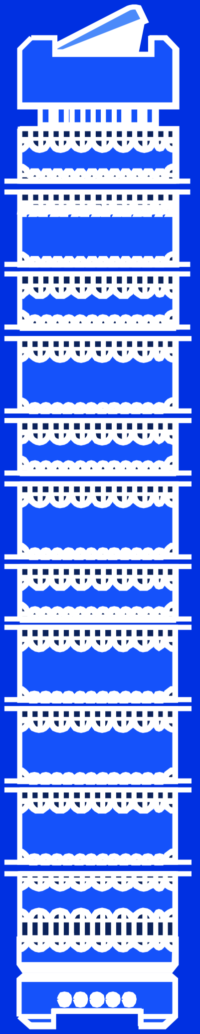
- Main life limiting mechanism is clad water-side corrosion
  - –new corrosion resistant cladding materials now in use
- New fuel rod designs increase effective fission gas plenum volume by various means, including use of hollow pellets
- Increasing axial heterogeneity of enrichment and poison distribution
- Pellet clad interaction failures in BWRs virtually eliminated by use of large rod arrays (eg 10x10 bundles) and liner cladding



Fuel assembly skeleton

- Potential failure mechanisms are mechanical growth/swelling of assembly components (eg. grids, support tubes, shrouds), vibrational damage and debris fretting
  - –improved designs restrain fuel rods more securely and benefit from improved understanding of materials behaviour under irradiation
  - –debris filters now routinely used, along with other fixes such as clad surface hardening in vulnerable locations, but room for further improvement

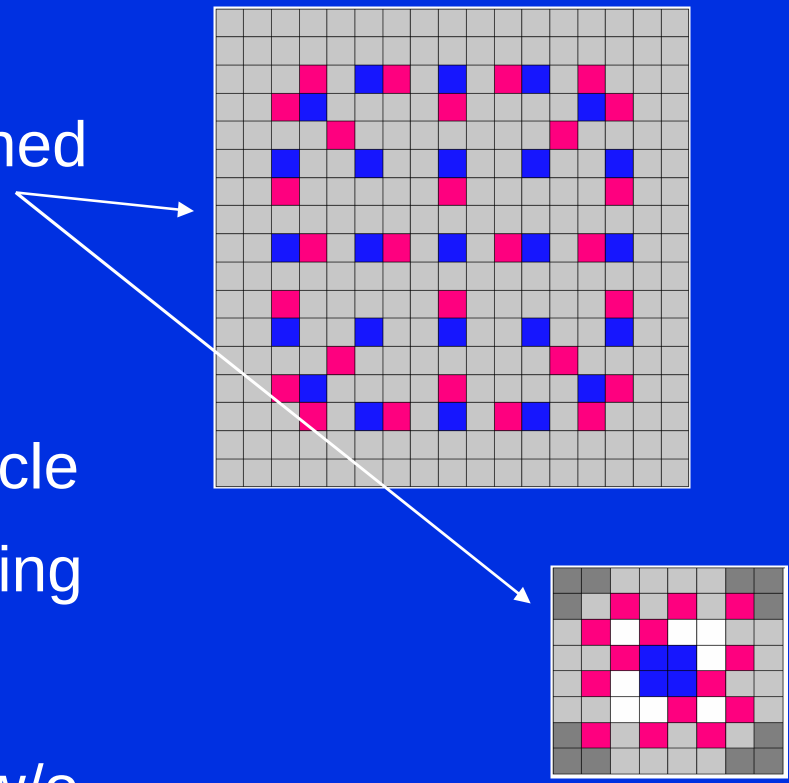




Fuel management

BNFL

- Trend towards ever more complex burnable poison radial and axial heterogeneity combined with increasing enrichment heterogeneity
- Also to more complex fuel management schemes designed to meet extended fuel cycle and discharge burnup targets while maximising margins to safety and operating limits
- Further development may be limited by 5.0 w/o criticality constraint in fuel manufacture
- Increasing use of MOX fuel to recycle civil plutonium and to disposition weapons plutonium



Evolutionary LWR fuel development

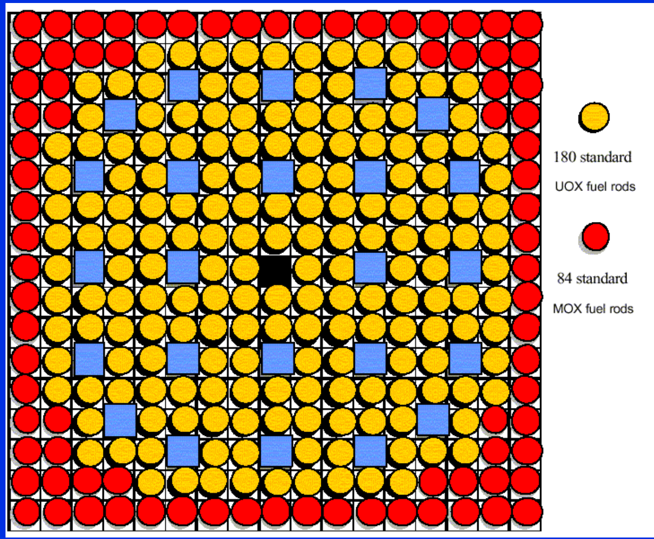
- Only a small fraction of work directed specifically at safety issues :
  - –usually fuel reliability is an economic issue for the utility
  - –most safety-related work is defensive in nature

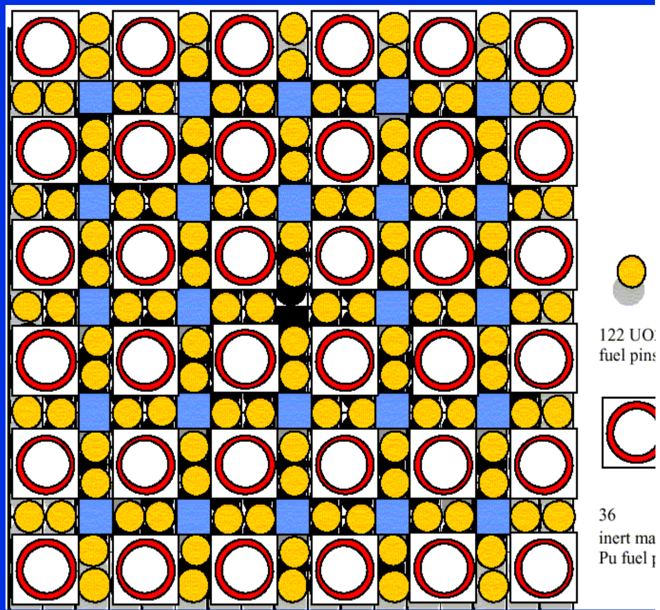
Radical LWR fuel developments

- Thorium fuels
  - –very active research field in EU and elsewhere
  - –aims to benefit from reduced long term radiotoxic potential and perceived proliferation benefit
  - –radical approach developed by Thorium Power Corporation with seed/blanket two component assembly design to maximise contribution from ^{233}U fissions
- Inert matrix fuels
  - –potentially can eliminate fresh Pu conversion, but difficulties demonstrating satisfactory physics performance and establishing fuel performance behavioural database

Radical LWR fuel developments

- Most active area is in plutonium assembly design, for increased Pu loading and net destruction :
  - –CEA MIX assembly uses enriched uranium as the main fissile driver, with Pu in a supplementary role
  - –CEA CORAIL concept uses central zone of UO_2 rods and outer MOX zone
  - –CEA APA design uses large diameter, annular PuN rods





Radical LWR fuel developments

- CEA have examined high moderation MOX assemblies to achieve more efficient utilisation of plutonium :
  - moderator/fuel ratio increased to be optimal for MOX
  - increases net Pu destruction
  - difficulties with multiple recycle
- Japanese research organisations examining low moderation PWR and BWR assemblies designed to establish LWRs as plutonium breeders :
  - intended for strategic independence prior to full fast reactor implementation

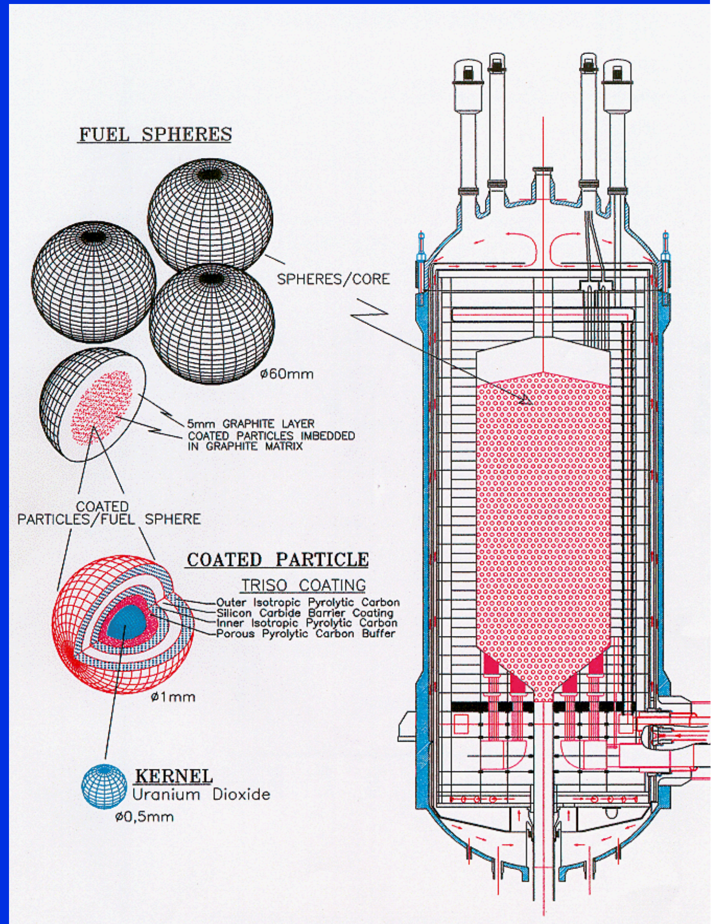
Radical LWR fuel developments

BNFL

- Radical fuel designs are high risk options for utilities
  - –long timescales for demonstrating reliable performance
  - –utilities need external incentives to pursue, even if there are theoretical benefits
- Most are options for 20 years from now

Fuel development for future thermal reactor systems

BNFL



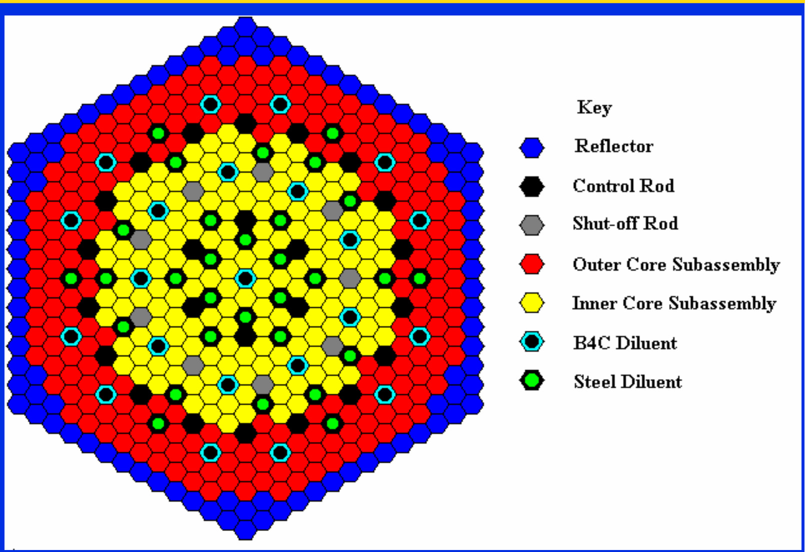
- Evolutionary LWRs identical cores to current LWRs
- TRISO fuel particles for Pebble Bed Modular Reactor (PBMR) and Gas Turbine Modular Helium Reactor (GT-MHR)
- Small modular reactors with low proliferation risk in response to US Dept of Energy Initiative (NERI) :
  - –long life cores modular (up to 15 years) with restricted access replaced as a unit
  - –inherent safety etc

Fuel designs for future fast reactor systems

- Japan & Russia still actively pursuing fast reactor research to establish strategic independence
- CAPRA-CADRA - fast reactor research effort in EU led by CEA since 1993 to investigate Pu burning, MA burning/waste reduction :
  - CAPRA-CADRA has examined all reactor types (LWR, HTRs, metal cooled fast reactors and gas cooled fast reactors, molten salt and ADS)
  - goal is to identify options available for sustainable fuel cycles in response to 1991 Law, by 2006

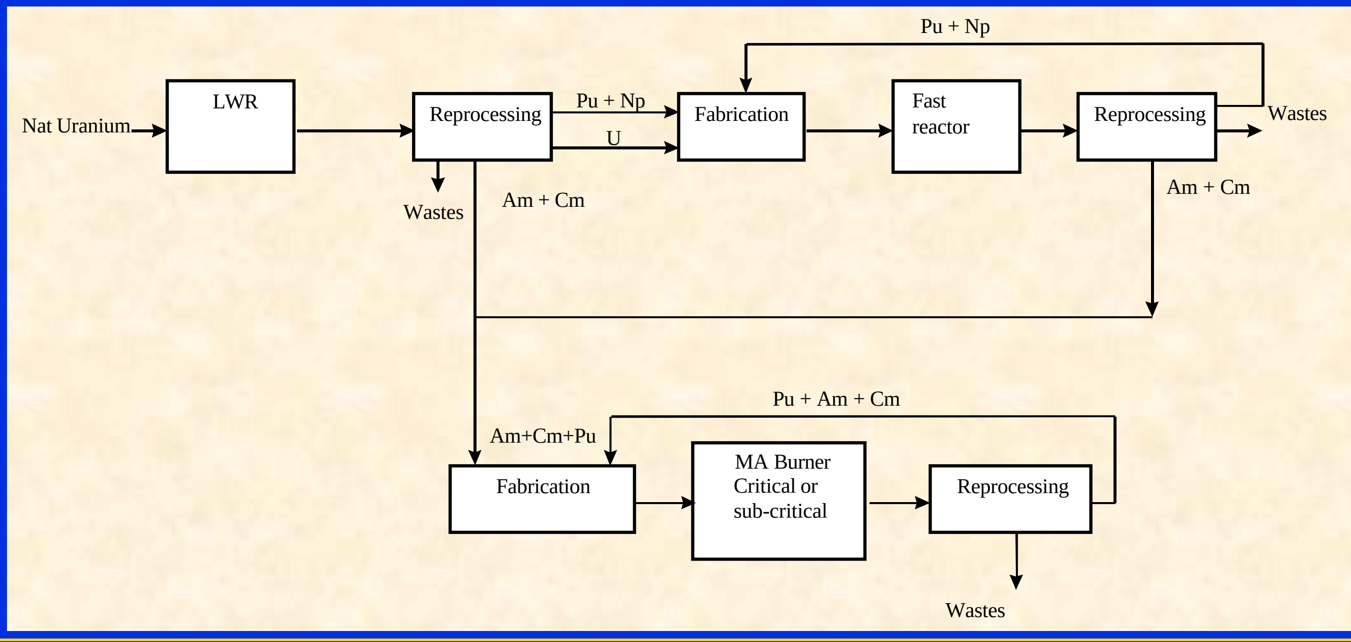
CAPRA-CADRA scope

- CAPRA-CADRA has examined variants of EFR designed to:
  - –maximise Pu consumption
  - –breed Pu
  - –burn MAs
- Other fast reactor variants (Pb-Bi cooled and gas cooled) also being examined
- Programme has demonstrated flexibility of fast reactors for Pu and MA burning and also the practical limitations

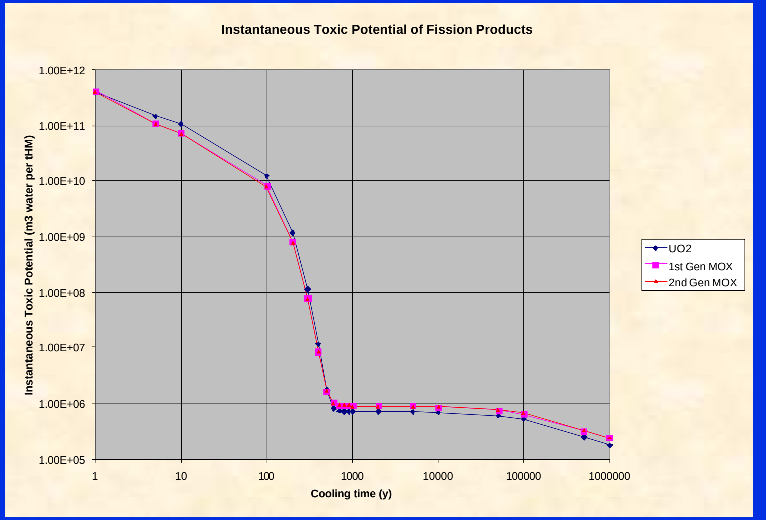


CAPRA-CADRA scope

- Includes analysis of scenarios for deployment of MA burning reactors
  - –Double stratum scenario
  - –Double component scenario



Minor actinide target fuels



- Designed to burn Np, Am and/or Cm and reduce long term radiotoxicity
- Homogeneous approach favoured for Np - ie Np incorporated in fuel
- Heterogeneous targets favoured for Am (and possibly Cm) - separate “dedicated” target assemblies containing Am or Cm in suitable chemical form
  - –moderated targets increase burn-out rate
- Extensive core physics studies have established technical feasibility

Minor actinide target fuels

BNFL

MA target fuel material	Type	Research activities
Oxide fuels		
$(Pu,Ac)O_2/UO_2$	Homogeneous	Basic properties, sample irradiations
$(Ac)O_2/PuO_2$	Homogeneous	Basic properties, sample irradiations
$(Pu,Ac)O_2/ZrO_2$ (zirconia needs to be stabilised with CaO, Y_2O_3 or MgO)	Homogeneous	Properties measurements, sample irradiations
$(Pu,Ac)O_2/Y_2O_3$	Homogeneous	Properties measurements, sample irradiations
$(Pu,Ac)O_2$/MgO Cercer fuel	Heterogeneous	Properties measurements, sample irradiations
$(Pu,Ac)O_2/CeO_2$	Homogeneous	Properties measurements, sample irradiations
$(Pu,Ac)O_2/MgAl_2O_4$	Heterogeneous	Basic properties
Nitride fuels		
((Pu,Ac)N/ZrN	Homogeneous	Properties measurements, sample irradiations
(Pu,Ac)N/YN or CeN	Homogeneous	Basic properties
Metal fuels		
U-Pu-Zr	Alloy	Properties measurements, sample irradiations
Cermet fuel (ceramic/metal)		
$(Pu,Ac)O_2$/W	Heterogeneous	Basic properties
$(Pu,Ac)O_2$/Cr or V	Heterogeneous	Basic properties
(Pu,Ac)N/Cr or V	Heterogeneous	Basic properties

Conclusions

- Clear division between :
  - –fuel R&D in support of utilities, driven largely by economics
  - –long term fuel R&D usually driven by strategic, environmental, sustainability issues etc, with practical issues such as economics
- Utilities need to ensure they do not lose sight of long term issues, such as sustainability, which may have to be addressed as part of the “cost” of future business
- Long term researchers need to be more aware of utility viewpoint

Conclusions

- Possible role for international bodies to help bridge the gap between short and long term research activities
  - –possible first step to arrange a forum specifically for this purpose and to identify research areas of common interest
  - –followed possibly by joint research activities
- Important for utilities to be able to share research costs